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Start-up Dynamics of Vertical Axis Wind Turbines: A Review

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Abstract. Vertical Axis Wind Turbines (VAWTs) are becoming increasingly popular for wind power extraction due to their simpler design, lower manufacturing and maintenance costs. The omni-directionality of these power generating machines make them more suitable for operation both under lower wind speeds and highly transient winds. The key wind power extraction component of VAWTs is their rotor, which is conventionally either Drag-based or Lift-based, with the latter being more widely studied in the published literature due to its higher power coefficient compared to its counterpart. The lift-based rotor comprises of aerodynamically profiled blades, while the drag-based rotor comprises of thin cup-shaped blades. The start-up of both these types of VAWT rotors has been an area of active research in the last decade. These studies have been conducted using numerical and experimental methods focusing on key parameters related to the start-up dynamics of VAWTs. Many of these research studies complement each other's findings, however, there are also a number of aspects where there are disagreements and/or significant knowledge gaps that need to be highlighted in order to accelerate scientific efforts strategically. In the present study, we aim to address these challenges through a thorough and critical review of the published literature on VAWTs' start-up dynamics, leading towards the identification of key knowledge gaps.

1. Introduction

The impact of climate change and the methods of combating its effects are some of the most important topics of the 21st century. Thomas [1] states that renewable energy sources have been identified as crucial tools in transitioning away from fossil fuels, with wind energy at the forefront as one of the most substantial contributors of clean energy. As a major renewable energy source, it is essential that wind energy technologies are effectively studied. Generally, wind turbines can be classified into Vertical Axis Wind Turbines (VAWTs) and Horizontal Axis Wind Turbines (HAWTs), according to their rotational axis. HAWTs consist of aerofoils fixed to a rotor that create a rotational motion around the central axis to power a generator. The rotational motion is a result of a lift force generated by air flowing over the aerofoils surface. As reported by Commons and Winslow [2], HAWTs provide the highest efficiency because of their ability to extract energy through their entire rotation. It is a requirement that HAWTs are positioned towards oncoming wind and hence require a yaw system. In terms of the start-up, although not the focus of this study, MW scale HAWTs' capacity factor ranges between 25% and 35% which the global research community is trying to increase in order to further reduce Levelized Cost of Energy (LCOE) and to provide power at cheaper rates.

VAWTs, on the other hand, may or may not consist of aerofoils, and are of two main types i.e. lift-based (Darrieus) and drag-based (Savonius) VAWTs, as shown in Figure 1. Lift based VAWTs operate on the same aerodynamics principles as HAWTs but are far less efficient as the energy extraction occurs only partially during its full rotation. Kragten [3] reports that lift-based turbines possess a large angle of attack variation, resulting in negative torque at certain points of revolution. Another challenge with lift-based VAWTs is that large fluctuation forces are present on the support structure during each revolution. Kumar et al [4] have reported that lift-based VAWTs display ineffective self-starting capacity which is aggravated by its common usage in urban environments comprising of irregular wind patterns. Drag-based VAWTs, as opposed to lift force, operate on the drag force and thus, do not require aerofoil shaped blades, which significantly reduces their manufacturing and maintenance costs. Wenehenubun et al [5] have found that in drag-based VAWTs, the concave section facing the wind catches the air, creating a force that rotates the turbine around its central axis, while the wind striking the convex section is deflected away. Thus, the drag-based VAWT turns due to the concave sections of the blades experiencing more drag force than the convex sections. Andrus [6] has reported that the drag-based VAWTs are simpler in design and relatively easy to manufacture, and do not require any specialised components. These turbines are safe to be operated in close proximity of each other due to their lower operational speed. Wong et al [7] have argued that drag-based VAWTs display more favourable self-starting characteristics than lift-based VAWTs, though at reduced efficiency.

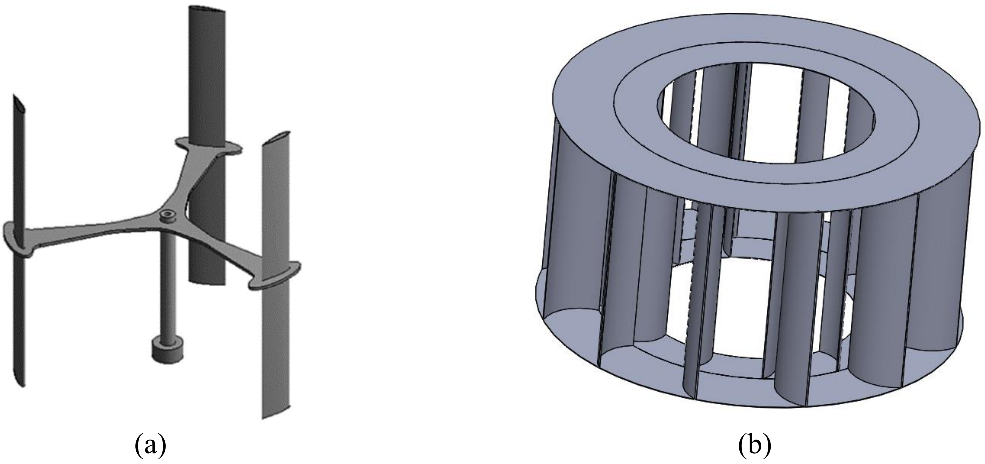

(a) (b)

Figure 1. (a) Lift-based VAWT [8] and (b) Drag-based VAWT [25]

While comparing distinct types of wind turbines, the question regarding their practical applications always arises. Due to their high efficiency, HAWTs are used in large-scale wind farms projects, both onshore and offshore, supplying electricity to the power grid. According to Repsol [9], onshore sites are primarily located at large steppes and coastal areas with high wind speeds. Wind turbines can also be used outside the farm environment and can be positioned in isolated locations far from grid access. Offshore farms work in a similar manner to onshore farms, however, can produce more power due to the winds being more frequent and undisturbed. As Islam et al [10] report, VAWTs are seldom used in windfarms due to their relative inefficiency but have found use in more niche applications due to their lower economy. Common uses for VAWTs are electricity production, pumping, purifying, friction heating, mixing and temperature regulation using vapor compression heat pumps. VAWTs can be used anywhere wind is blowing, due to their omnidirectional design and can supply individual homes and facilities with power. Lift-based VAWTs are typically used in these applications except when reliability and cost are of more importance over efficiency, in which case drag-based VAWTs are preferred.

2. Start-Up Dynamics of Vertical Axis Wind Turbines

The start-up of a wind turbine is referred to as the regime from when the turbine starts rotating from rest, up-till when it reaches its peak rotational velocity i.e. steady performance for that particular wind speed. The start-up of wind turbines is directly linked to their capacity factor, which is the ratio of power generation from the turbine to its maximum possible/theoretical power generation. Thus, a turbine with enhanced start-up will start rotating at lower wind speeds, will reach its peak performance quickly and will have higher peak rotational speed. It is evident that the start-up of a wind turbine is extremely crucial to its power generating capability, and eventually on the unit cost of power from it. The capacity factor of wind turbines is lower than nuclear, hydro, geothermal, natural gas, and coal-based power generation technologies.

Start-up dynamics, conventionally, encompass the evaluation of turbines' rotational speed over time. It is well reported in published literature that the start-up dynamics of different types of wind turbines is significantly different. Even for the same type of turbine, for example lift-based VAWTs, there is no universal consensus on the start-up dynamics. In some studies, it is reported that VAWTs can self-start, while according to other studies, they cannot. The aim of this paper is to bridge this gap in the literature by conducting a critical review of the published studies on the start-up dynamics of VAWTs, both lift-based and drag-based, to highlight the parameters that dictate their start-up dynamics and to build consensus. Thus, the following sections detail the start-up dynamics of lift-based and drag-based VAWTs respectively, based on the published literature.

2.1. Lift-based VAWTs

One of the pertinent challenge the researchers have faced while analyzing the start-up dynamics of lift-based VAWTs is whether they can self-start or not. Researchers have disagreed on how to define self-startup. Ebert and Wood [11] state that a turbine can self-start only if it can accelerate from rest to the point where it starts to extract significant wind power. Kirke [12] provides a similar definition, whereby a turbine is considered as self-starting if it can accelerate from rest to a point where it can produce useful power. Both authors do not clearly define the terms significant and useful powers. Furthermore, Sun et al [13] state that a turbine is self-starting if it can reach passive rotation without external assistance. Regardless of how the self-startup is defined, Hill et al [14] have reported that there is a disagreement on whether lift-based VAWTs can self-startup.

When quantifying the start-up dynamics of lift-based VAWTs, similar to the one shown in Figure 1(a), Hill et al [14], Asr et al [8] and Celik et al [15] have reported that there are four main stages of self-startup. The curve obtained by Hill et al [14] can be seen in Figure 2. The first stage during the start-up is when the turbine starts accelerating from rest (termed as 1st acceleration) whereby the rotor angular speed increases roughly linearly with time, due to the drag force exerted on the rotor blades. The turbine's Tip Speed Ratio (λ) reaches 1.25 at the conclusion of stage 1. The acceleration stage is followed by a long plateau region (1st plateau) where the rotational speed of the turbine increases gradually. This stage is then followed by a rapid acceleration of the turbine (2nd acceleration), due to the aerodynamic lift being exerted on the blades. Finally, the last stage of start-up is the 2nd plateau region, which corresponds to constant rotational speed and steady performance of the turbine. It is noteworthy that at the end of the 2nd acceleration stage, the turbine has reached its maximum rotational speed ($\lambda = 3.1$) for that particular wind speed and thus, the start-up process concludes at the end of 2nd acceleration. Asr et al [8] have observed complex flow field during lower λ values of the turbine, due to each blade experiencing low and high angles of attack during each rotation. At higher λ values though, the flow fields associated with the turbine are more uniform.

Kirke and Lazauskas [16] state that variable pitch blades, cambered blades, inclined blades, helical blades, and increased solidity can all help improve start-up of lift-based VAWTs. Mitchell et al [17] used a novel vented blade design which led to improved self-starting capability and overall performance at $\lambda < 0.5$. The vented aerofoil features vents on the trailing edge which increase drag at Angle of Attack (AoA) < 90°, without reducing lift. Asr et al [8] examined the start-up characteristics of symmetric and cambered aerofoils of different thicknesses, with a wide range of pitch angles. Two cases of variable blade pitch angle are shown in Figure 2. It had been reported that when using a cambered NACA 2418 aerofoil with an outward pitch angle of 1.5°, a 27% reduction in start-up time was observed. Interestingly, in both these cases, the initial acceleration and the 1st plateau region region has been observed, but the 2nd acceleration and the subsequent plateau regions were not present. Zhu et al [18] investigated the self-starting aerodynamics of a VAWT and found that a turbine with a fixed pitch blade angle of -2.5° resulted in faster self-startup and higher overall power coefficient. Both these studies (Asr et al [8] and Zhu et al [18]) agree about the effect that pitch angle has on self-startup time, however it must be noted that Zhu et al [18] observed all four stages during the start-up of the turbine.

According to Celik [15], the number of blades is one of the most important parameters affecting the start-up of H-rotor VAWTs. The authors found that a turbine with two-blades was unable to self-start but turbines with three, four and five blades were able to self-start, with the five-blade turbine demonstrating the fastest start-up time, as shown in Figure 2. Thus, it can be safely said that as the number of blades increases, the likelihood that a turbine self-starts increases and the time taken to self-start decreases. However, it should be noted here that as the number of blades of the turbine increases, the cost of the turbine also increases. Thus, improving the start-up dynamics of VAWTs has financial consequences. Another start-up characteristic of two-bladed VAWT observed was that the start-up curve didn't show the 2nd acceleration stage. Dominy et al [19] developed a numerical model to determine the parameters that govern the self-starting capability of a lift-based turbine and observed that a three-bladed H-rotor was able to self-start irrespective of its initial orientation. Hill et al [14] also reported that a three-bladed VAWT was able to self-start irrespective of its starting position. It has however been reported that self-startup of a two-bladed VAWT is dependent on its initial starting position. From Celik [15] and Dominey et al [19], it is clear that there is disagreement on the start-up of two-bladed turbines. Tavallaeinejad et al [20] has numerically investigating the start-up dynamics of a two-bladed H-rotor in order to improve its start-up dynamics by attaching flexible additional/secondary blades to the trailing edges of the primary blades. Significant improvement in the start-up dynamics of the VAWT has been reported however, it should be noted that these additional blades have a significant cost associated with them and thus, it is clear that any external interventions in order to improve the start-up dynamics of VAWTs have cost implications.

Eboibi et al [21] investigated the influence of solidity on the start-up performance and flow fields associated with a lift-based VAWT. It has been reported that the self-starting capability of a VAWT can be enhanced by appropriate selection of the VAWT's solidity. The solidity of a wind turbine is defined as the ratio of its blade area to the turbine's swept area and can be increased by increasing the number of blades. Mitchell et al [17] found that the rotor of a lift-based VAWT would be able to self-start if six blades were used to increase the solidity. Sun et al [22] investigated the effects of blade number and azimuthal angle on the starting performance of a hydrokinetic turbine. It was found that a four-bladed turbine showed quicker start-up than two and three-bladed configurations. The optimum azimuthal angle was found to be in the region of 100° - 120°, regardless of the number of blades. Kirke and Lazauskas [23] found that by increasing the chord length of a hydrokinetic turbine, the solidity increases, and the self-starting capability is improved. Zhu et al [18] found that self-starting time decreased when the maximum rotor solidity was within the range of 0.6 - 1.0. Sun et al [13] carried out investigations on three-bladed and five-bladed configurations of lift-based VAWTs with variable pitch blade angles. It has been reported that all configurations are able to demonstrate self-startup. It has been further reported that at low flow velocities, the number of blades did not affect the self-starting time. However, at higher wind velocities, the self-starting time increased as the number of blades increased. Therefore, it can be concluded that higher the solidity of a VAWT, the faster it will be able to self-start.

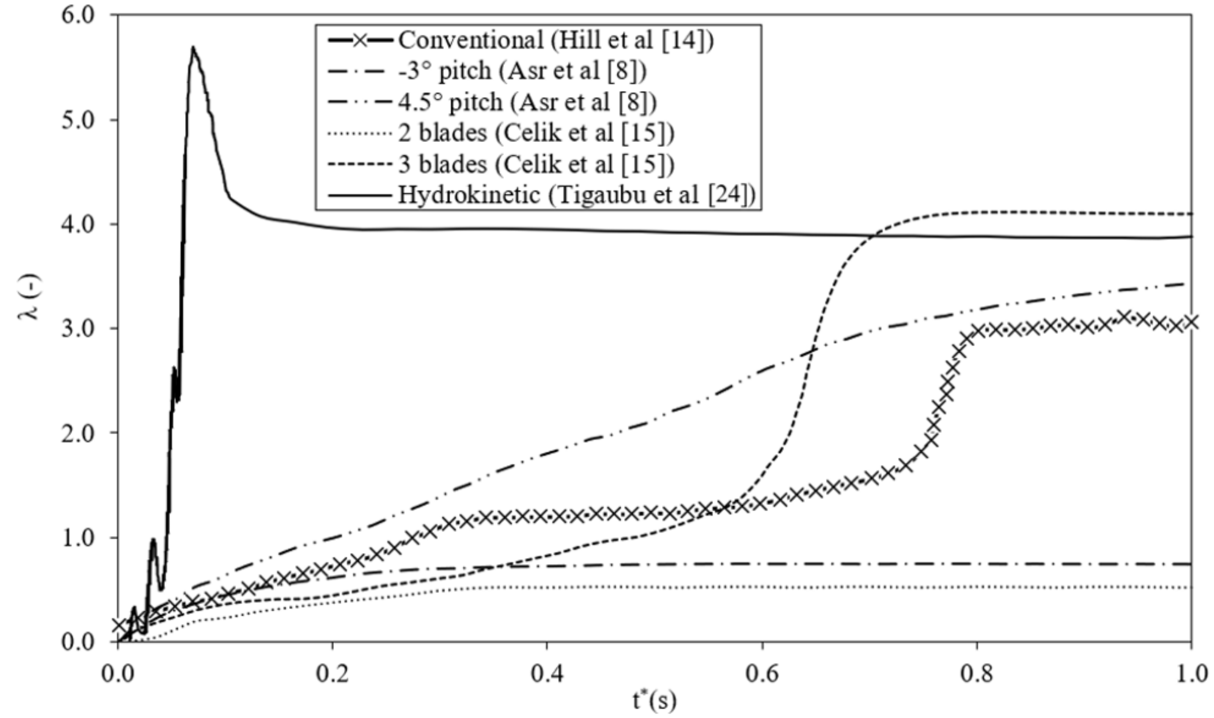


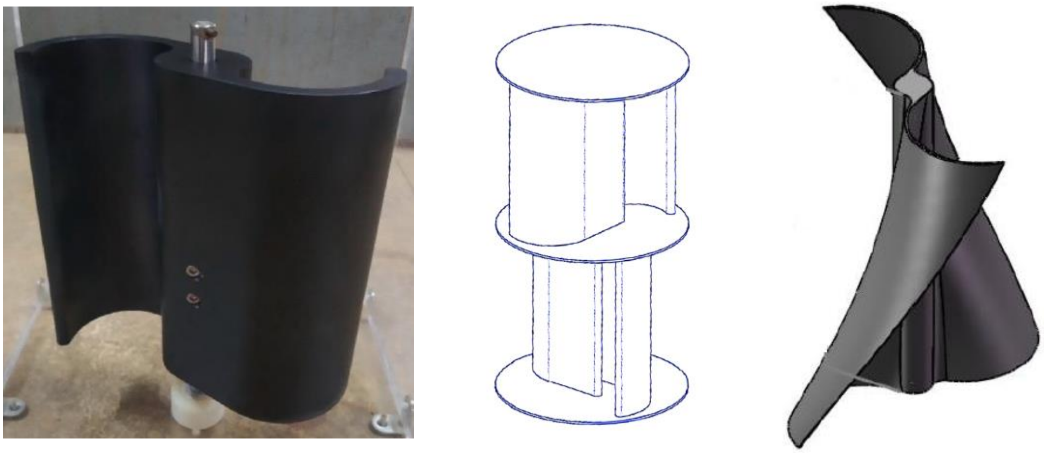
Figure 2. Stages during start-up of lift-based VAWTs

Tigabu et al [24] observed significantly different start-up dynamics for a lift-based hydrokinetic turbine, as can be seen in Figure 2. It has been reported that during the start-up of the turbine, four stages have been recorded. These four stages of start-up are i) initial acceleration, ii) overshoot, iii) deceleration, and iv) runaway. The initial acceleration and final runaway (or 2nd plateau region) are the same as reported by Hill et al [14]. According to Goude [25], overshoot is an effect that occurs when the wake formation does not stabilize immediately after the turbine changes its rotational speed. In terms of start-up dynamics, it is represented by a distinct peak in the λ curve, where overshoot means that the λ increases beyond the steady-operational λ of the turbine. This overshoot is followed by a deceleration, lowering the λ to steady-operational value. The overshoot phenomena has not been reported in any literature regarding lift-based VAWTs, which highlights the effect of fluid properties on start-up dynamics.

An important point to note here is that Tigabu et al [24] carried out numerical simulations on the hydrokinetic turbine, where the inertia of the turbine is based solely on the mass moment of inertia, and the bearing friction and generator loads are not considered, which by default were present in case of Asr et al's [8] experimental work. Sun et al [13] incorporated the bearing friction and generator loads in their numerical investigations through the introduction of external loading coefficient (C_{load}). However, they assumed the value of this coefficient instead of measuring it experimentally. This leads to a very important conclusion when modelling wind turbines numerically i.e. an accurate value of inertia is of utmost important when quantifying the start-up dynamics of VAWTs, else the numerically predicted steady-operational λ will be significantly higher. Tigabu et al [24] did evaluate the effects of inertia (not considering C_{load}) of the hydrokinetic turbine on its start-up dynamics and have reported that by considering lower values of turbine inertia, the start-up time of the turbine reduced significantly. The authors also found out that shorter start-up times lead to higher overshoot experienced by the turbine.

2.2. Drag-based Rotors

Studies investigating the start-up dynamics of drag-based VAWTs are severely lacking in the published literature and hence, the review presented here has significant element of drag-based hydrokinetic turbines. A potential reason for very few research studies on the start-up dynamics of drag-based VAWTs could be their variable design configurations as the blades are not based on aerofoils. Thus, many different types of drag-based rotors have been reported in the published literature, focusing primarily on their steady performance characteristics. Some of these designs are shown in Figure 3 and in Figure 1(b).



(a) (b) (c)

Figure 3. Different lift-based rotor designs (a) Conventional rotor [29], (b) Two-stage rotor [30], (c) Spiral rotor [27]

Asim et al [26] carried out numerical investigation on the start-up of a 12-bladed drag-based VAWT, shown in Figure 1(b), with the aim to evaluate the effects of stator blades on the start-up of the VAWT. The blades considered, both rotor and stator, are made of thin sheets of aluminum and are curved. For numerical investigations, only the mass moment of inertia of the turbine has been considered. The stages of start-up that have been reported are i) initial acceleration, and ii) steady operation (plateau region), as shown in Figure 4. The same stages have been observed after integrating the stator with the rotor, with the differences that i) the λ of the turbine increased from 0.65 to 1.45 for the same wind speed, and ii) the peak λ is achieved at a later time instance. It has been further reported that due to no generator load on the VAWT, the average torque output from the VAWT was zero. Mu et al [27] investigated the effects of modifying a two-bladed drag-based rotor by twisting the blades 70° to create a spiral turbine, as shown in Figure 3(c). The investigation also considered a traditional drag-based rotor as the baseline model (similar to the one shown in Figure 3(a)), which failed to self-start at AoA between 120° and 170°, whereas the spiral rotor self-started at AoAs between 0° and 180° subject to windspeeds between 6m/s and 12m/s. Start-up dynamics observed in case of both the traditional and spiral rotors match with the ones obtained by Asim et al [26] with the difference that higher λ was achieved (compared to Asim et al's [26] rotor only model). Furthermore, it has been reported that increasing the wind speed increase the initial acceleration to steady operation of the rotor. Thus, it can be said that regardless of the design of the drag-based rotor, the start-up dynamics (qualitatively) remain the same.

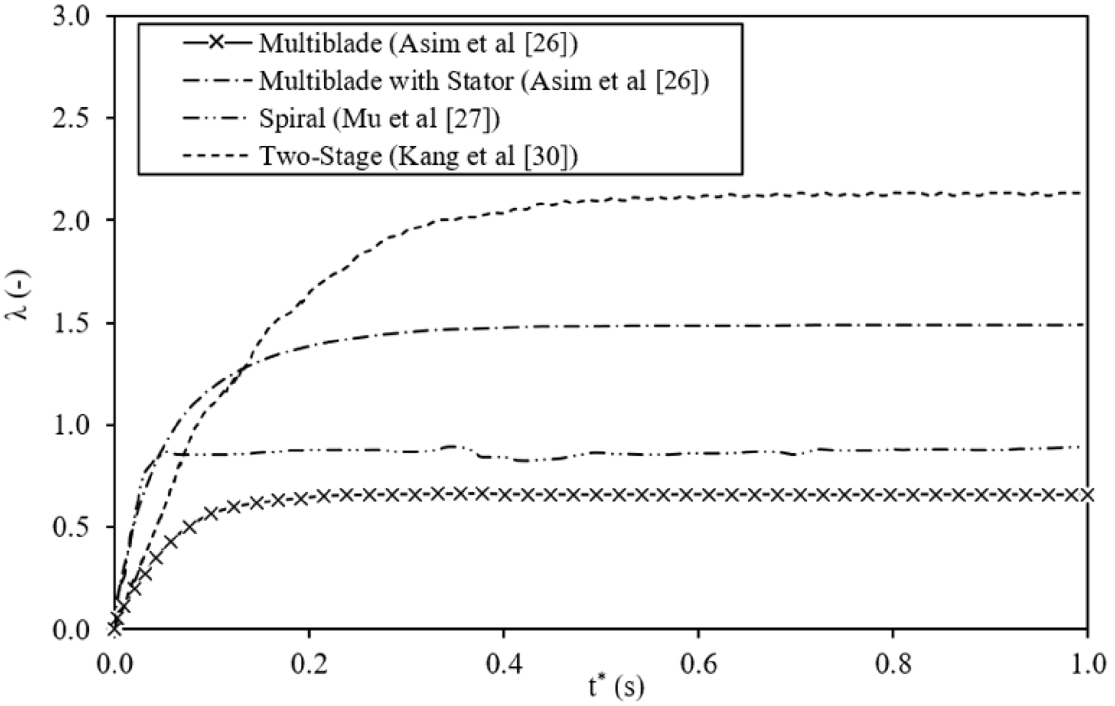


Figure 4. Stages during start-up of drag-based rotors

Ushiyama [28] carried out numerical investigations on the start-up and steady performance of several drag-based rotor configurations. It has been reported that as the rotor's aspect ratio increases, the rotor reaches its steady performance earlier, which is in-line with the observations of Mu et al [27]. Evaluating the effects of overlap ratio, it has been reported that increase in overlap is reflected in slightly higher steady operational speed of the rotor. Comparison of Bach type rotors show similar start-up as the conventional rotors, though Bach type rotors achieve higher operational speeds. Results also indicate that three-bladed rotor's start-up is slower compared to two-bladed rotor. Zhao et al [29] numerically investigated the start-up dynamics of a two-bladed drag-based hydrokinetic rotor, shown in Figure 3(a), at multiple azimuth angles (starting orientations). It has been reported that initial orientation of the blades dictates whether self-startup would occur or not, with some orientations producing negative torque values, resulting in self-startup failure. Start-up occurred at AoA of 40° and comprises of the same four stages as observed by Tigabu et al [24]. Start-up failure was recorded at AoAs of 70° and 150°, providing insights into the dead band range of AoAs. Similar to the dead band range of AoAs observed by Mu et al [27], the initial acceleration of the rotor is shortly followed by deceleration until a slight reverse rotation is noticed. The rotor demonstrates repetition of both these stages in the dead band range, showing a sinusoidal pattern in the rotational speed of the rotor. The positive and negative drag forces experienced by the rotor blades, on average, balance out, with fluctuations experienced due to rotor's inertia.

Kang [30] investigated the start-up dynamics of a single and two-stage drag-type hydrokinetic rotor numerically. The two-stage rotor, shown in Figure 3(b), is formed by splitting a conventional single-stage rotor in half using an end plate and rotating the blades in one of the stages by 90°. An upstream guide vane (stator) was also incorporated in the design to support self-startup, as carried out by Asim et al [26] for a 12-bladed rotor and by Mosbahi et al [31] for a 3-bladed rotor. The results clearly demonstrate that the dead band vanished through the introduction of the guide vane. Start-up of single stage rotor had shown similar characteristics to Zhao et al's [29] rotor as essentially both these rotors are quite similar to each other in design. Start-up of two-stage rotor also shows similar patterns with the difference that the rate at which the steady operation of the rotor is reached increases. It is thus clear that for all the different design configurations of drag-based rotors considered, both aerodynamic and hydrokinetic, the start-up dynamics remain the same qualitatively. Comparing the start-up dynamics of drag-based rotors with lift-based rotors, in-light of the stages reported by Hill et al [14] and others [8, 15-17], it can be concluded that the drag-based rotors demonstrate the same characteristics as the first two stages of lift-based rotors, and that the driving force is the aerodynamic drag. The lift-based rotors then go one step forward with another acceleration stage, which is the result of the aerodynamic lift generated by the rotor blades.

3. Conclusions and Future Recommendations

A thorough and systematic review of published literature regarding the start-up dynamics of vertical axis wind turbines has been conducted in the present study with the aim to highlight the similarities and differences between lift-based and drag-based rotors. The review makes use of studies carried out both experimentally and numerically. The literature available on the start-up dynamics of VAWTs is still in its infancy, and especially, the literature on the drag-based rotors is severely lacking. From the discussions carried out in this study, it can be concluded that both lift-based and drag-based VAWTs can self-start when configured properly. This can be achieved through the increase in the rotor solidity, which can be achieved by increasing the number of rotor blades. Disagreements have been found in the literature on the effects of blade pitch angle, with regards to self-startup of VAWTs, and thus, the use of variable pitch blades is recommended. Moreover, this particular area requires more in-depth characterisation to fully understand the effects that blade pitch angles have on self-start-up of VAWTs. The start-up of lift-based VAWTs has been shown to depict four stages i.e. two accelerations and two plateau regions. For all self-starting lift-based VAWTs, the same start-up dynamics have been recorded, however, for lift-based hydrokinetic rotors, the start-up dynamics are significantly different.

The self-startup of drag-based VAWTs is still not clearly understood and thus, more scientific efforts are required in this context. One aspect however is clear that the inclusion of a stator/guide vane enhances the self-startup capability of the drag-based rotor and helps achieve higher tip speed ratios. Moreover, increasing the rotor solidity and through the use of spiral blades, the self-startup of drag-based rotors can be significantly enhanced. The start-up dynamics of drag-based rotors are, at the same time, similar yet different to lift-based rotors. Drag-based rotors' start-up dynamics depict the same first two stages as observed in case of lift-based rotors, but this is not followed by another acceleration stage. This is because the first two stages of both these types of rotors is due to the drag force acting on the blades, while the second acceleration in case of lift-based VAWTs is due to the aerodynamic lift experienced by the rotor blades. Drag-based hydrokinetic rotors depict the same start-up characteristics as aerodynamic rotors, as opposed to lift-based aerodynamic and hydrokinetic rotors.

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